Theoretical approach for a multi-operator synergistic utility planning and its real-life implications

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***Abstract*—More often than not, maintaining a utility network requires opening up streets which results in traffic diversions and traffic jams in turn leading to additional nuisance for urban citizens. By aligning the planning of different utility providers, additional synergies can be achieved, which will not only result in fewer nuisances for the city in general, but may also lead to clear cost savings for the involved parties. Additionally, utility operators teaming up will also lead to safer work conditions, and less service interruptions due to unintentional damages. In this publication we present a multi-objective multi-actor approach to optimally reschedule the planning of a set of utility providers resulting in up to 32% more works executed in synergy and up to 46% more weeks of cooperation. Additionally, by verifying our approach with people with hands-on experience in utility network planning, we have managed to pinpoint a number of real-life implications; each of these issues have been discussed and when possible, approaches to tackle these issues have been proposed.**

***Keywords*—synergy, synergistic planning, network planning, techno-economic evaluation, utility planning**

I. INTRODUCTION

Synergy in utility (road) works takes on many forms and can offer multiple benefits. Better planned utility works result in less traffic problems, less hinder for the city environment and can result in economic gains for all involved parties. Additionally, as utility operators cooperate more closely, risk assessments can be drafted conjointly which results in safer work conditions and lowering the chances of unintentional damages which would lead to service downtimes. Finally, in case any unintentional damages still occur, repairs will be executed faster leading again to more safety and less hinder to the end customers and the city. These synergies can be obtained in a variety of ways:

1. By (optimally) sharing utility ducts, only one duct is created for multiple utility networks, this way the cost linked to digging the duct and (if applicable) repairing the pavement can be shared, which results in clear cost reductions. This approach is easily applied to a greenfield situation, but harder to apply in a brownfield situation since any previously installed cables have to be taken into account [1]-[4].
2. A second type of synergy is typically driven by an accelerated rollout of a new technology (e.g. fiber) to a city's main buildings such as governmental offices, libraries or schools. The rollout results in opening up a lot of streets in a short time span which presents other utility operators the opportunity to perform maintenance to the existing infrastructure or even install additional equipment [5]. This approach should not be considered a joint-rollout (as discussed next), but rather as a one operator rolling out a network and other utility operators joining in, rescheduling works that were already planned.

The first two approaches allow any utility operator to decide to execute a utility work in synergy, e.g. using duct sharing, on a case-by-case basis; other approaches are rather based upon long-term planning/cooperation between two (or more) utility providers:

3. A number of these long-term examples can be found for fiber networks that are being installed together with or even in the water or sewage network. This way, two networks are actually installed as one, in which digging costs are again strongly reduced or even almost completely negligible if fiber is installed in an existing water/sewage network [1][6].
4. Another way for telecom operators to deploy fiber is by installing fiber cables on existing (high-voltage) power lines. This way, the existing supporting structures can be re-used, offering again high cost savings [7].

The long-term approaches (3 and 4) will most likely have a strong and extensive planning in which cooperation and its benefits have clearly been defined from the start. The other approaches (1 and 2) are more flexible and any set of utility providers can decide to join in when possible, even on a case-by-case (e.g. a single street) basis. This case-by-case cooperation requires utility operators to share their internal planning either publically or towards an external party, so

other operators can look into it and alter their planning accordingly.
In reality however, utility operators usually publish their plans to work on a specific location only weeks or a few months in advance. Because of this short-noticed, decentralized approach only small amounts of ad-hoc collaboration can be achieved. In order to obtain more collaboration, an external centralized party should be in place, collecting data from all utility operators and making up one synergistic planning involving all utility operators.
Making up this kind of synergistic planning is a complex problem. On one hand, the planning of thousands of works should be considered (problem size), while on the other hand it is important to keep in mind the original planning of each of the utility providers and apply their planning preferences as much as possible (problem constraints).
In this paper, we propose a synergistic evaluation model, implemented using a genetic algorithm as a basic prototype, present some case results and reflect on the proposed model and list possible improvements.
The remainder of the paper is structured as follows: In paragraph II, we go deeper into the used data and the earlier mentioned planning preferences. Paragraph III describes the proposed synergistic model and the parameters that are used to evaluate this multi-actor planning. In paragraph IV we discuss a prototype implementation of the synergistic model using a genetic algorithm. Next we show some real-life case results in paragraph V. Afterwards, in paragraph VI we discuss a number of practical implications we have learned by discussing this theoretical approach with utility providers in Belgium. Finally paragraph VII summarizes this paper.

II. PROBLEM DEFINITION

Our goal was creating an algorithm generating an optimized planning for multiple utility providers, so utility works on the same location (e.g. same location in a street) or works near each other (e.g. each on one end or side of a street) are executed in synergy. To do so, the individual planning and planning restrictions of each of the involved utility providers are considered. Table 1 shows the parameters considered per work. For the remainder of this paper, the term *work* will be used as shorthand for a *utility construction site.*

Table 1: Metadata linked to a utility work

Parameter	Remarks
Location	A polygon representing the area of the work
Operator	Utility operator executing the work
Start & End	Originally planned start and end date of the work
Type	Textual description: e.g. sewage work
Planning status	Detailed planning or unplanned

While each utility provider has one general goal, e.g. providing water services, its goal can exist of a number of different tasks (which will be referred to as *types*), e.g. providing water delivery to houses and taking back wastewater. For each of the involved operators, and for each combination of planning status and type (Table 1), planning restrictions can be configured using time windows. Time windows are defined as a number of weeks a work can be scheduled earlier or later without having a negative effect on the planning (timing windows can be asymmetric, the allowed number of weeks earlier can differ from the number of weeks later); this is represented in Figure 1, as long as the start of the work is scheduled within the time window, no penalties will be applied (as discussed in III.B). These planning windows are introduced so the algorithm can better reflect the reality. Once the detailed planning of a work has been made, rescheduling becomes hard (if not impossible) since the planning of the work has been announced publicly and resources have been allocated accordingly. Therefor time windows for works that have been planned in detail will be set be very narrow, reflecting the inflexibility of the planning.

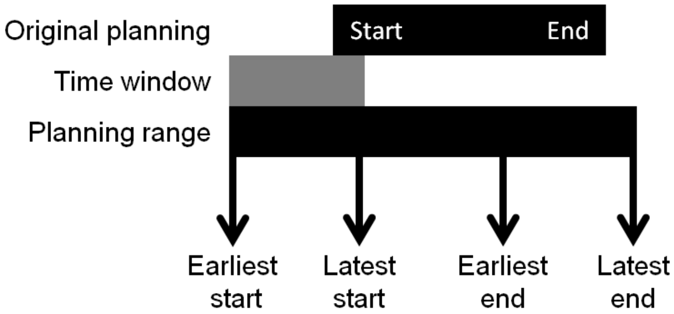

Figure 1: The time window defines how much earlier/later a work is allowed to start

Since it’s unlikely that an automatically generated planning will be used directly and unchanged by all utility operators, we are currently looking for a way to easily generate an optimized planning, starting from the existing planning and a set of input parameters; this new planning can then serve as input for discussion for the utility providers to alter their planning.

III. SYNERGY EVALUATION MODEL

In order to generate an optimized synergistic planning for multiple utility providers, the evaluation model should validate both the resulting planning per operator (whether the planning is practically feasible for each operator independently) and as a whole (in order to determine the total amount of synergy obtained). As the goal of this optimized planning is to reduce the total cost for all involved utility providers, it would make sense to score a newly generated planning by calculating the total cost for executing all works, taking into account that executing multiple works in synergy results in cost reductions. This, however, would imply that all utility providers share all budget information, which was impossible to obtain at this moment (if ever).
As an alternative, we have developed a point-based system, which consist of two pillars, as represented in Figure 2. The

first pillar focuses on scoring the planning of each utility provider using the earlier mentioned planning restrictions (which will be referred by as *single-actor evaluations*), while the second pillar scores the actual synergies (*multi-actor evaluations*).

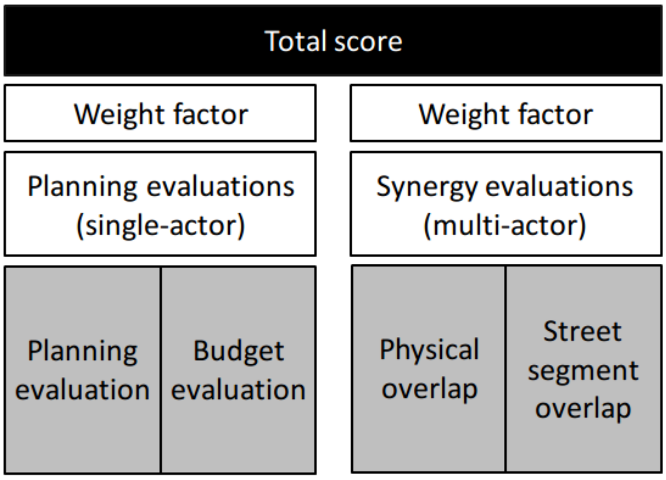

Figure 2: The fitness function consists of two weighted pillars, which respectively exist of single-actor and multi-actor evaluations.

A. *Calculating and steering of the best solution*

Within the proposed evaluation model, each evaluation generates a score per work. Afterwards, the total of each evaluation is recalculated to a value between 0 and 1 per operator. This has two major benefits: 1) additional evaluations can easily be introduced in the algorithm and 2) the unweighted sum of the pillars (Figure 2) is for each utility operator between 0 and the total number of evaluations (0 and 4 at the moment (2 single-actor and 2 multi-actor evaluations) which means that the weight of each utility operator in the model is by default equal.

In order to further steer the algorithm either to better match the preferences of the utility operators and their planning or ether to obtain more synergy, the model can be configured to use a weighted sum (not an unweighted one). In this weighted sum, the weight of each evaluation can be configured to match its importance. Additionally, a weight factor has been introduced to alter the impact of each individual utility operator in the model (in other words, the planning or preferences from one utility operator can be considered more important). Whether the weighting of utility operators *should* be altered is discussed in section VI; for the presented use cases the weights have not been altered (all have been set equally). In the next paragraphs, both types of evaluations (single and multi-actor) are discussed in detail.

B. *Single-actor evaluations*

The first set of evaluations validates the planning per utility operator; these evaluations score the newly generated planning compared to the original planning and the timing constrains. If the timing constrains have been set very narrow (as discussed in II) and the newly generated planning differs greatly from the original planning, the score as calculated by the evaluation model will reflect so. In the current version of the model, two types of single-actor evaluations are included.

1) *Planning evaluation*

The first type of evaluation scores each work based upon the original planning, the newly proposed planning and the timing constraints as discussed in II. This evaluation is split in two parts and respectively evaluates works that have been rescheduled earlier (resp. later) in time. As long as the proposed planning is within the planning range (Figure 1), no penalty is given. When exceeding these constraints, a penalty (meaning a negative score) is calculated as following:

$$penalty = -(\#WeeksOutOfRange * p)^{f} \tag{1}$$

The parameter (p) and the factor (f) are configurable per utility operator and per evaluation (earlier and later in time); this way the preferences of each utility operator can be reflected. Both values are by default set to 1. A simple example to clarify:

- Type A is a short type of work which can easily be rescheduled and little to no penalization should be in place. The parameter p can be set to 1 or even lower, f to 1.
- Type B is a critical type of work, has a very small time window and thus should be penalized severely. The parameter p can be set to 5 or higher f to 2 or higher..

2) *Feasibility of yearly budget evaluation*

The second single-actor evaluation scores the budget of each actor. As mentioned earlier in section II, we do not possess financial information of each separate project nor of the utility providers. As a solution we calculate a budget expressed in kilometer per year. When reading the original planning, we calculate the number of kilometers of work executed per year per operator. When evaluating a possible solution, we analyze the new planning, calculate the amount of kilometers of work executed per year, compare it with the original planning and calculate the relative deviation per year as shown in Figure 3.

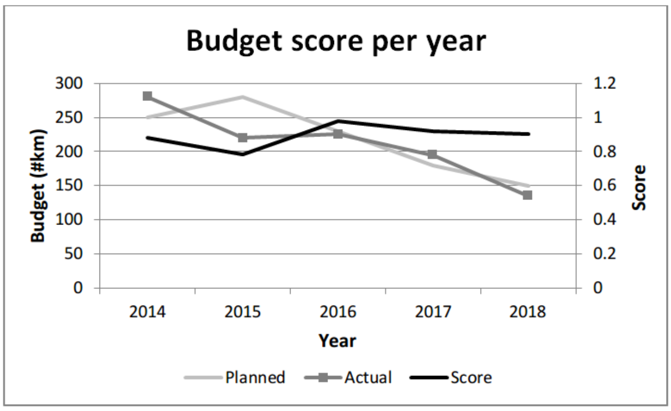

Figure 3: The second single-actor evaluation scores each actor's budget (expressed as a number of km) for each relevant year.

C. *Multi-actor evaluations*

The second pillar focuses on scoring the synergy gains of the newly generated planning and currently contains two multi-actor evaluations which evaluate the synergy obtained by executing two works together. We currently have considered two types of obtaining synergy. Firstly, physical overlap (in which two works physically overlap partly or entirely) and secondly street segment overlap (in which two works do not overlap physically, but are executed on the same street segment, e.g. each on one end or side of a street).

Tough it's possible for more than two works to overlap, the model only evaluates the overlap of two works at a time. This way, the evaluation functions can be simplified a lot. When an overlap consists of more than two works, each unique pair of works is calculated and is evaluated separately, e.g. when evaluating 3 physically overlapping works (A, B, C), we will evaluate (A, B), (A, C) and (B, C). The result of each evaluation is a score for each work; this way we can keep track of how good a solution scores for each utility operator separately.

Both evaluations as expressed in equation (2) and (3) have a parameter (p) and a factor (f) which are configurable per utility operator and per evaluation (physical and street overlap); this again allows the algorithm to reflect the preferences of each utility operator as much as possible. Both values are default set to 1.

1) *Physical overlap*

The first evaluation scores two physically overlapping works, by looking into both the quantity of physical and time overlap.

$$score = (timeoverlap * physicaloverlap * p)^{f} \tag{2}$$

The time overlap and physical overlap are the relative overlap (of the physical area and executing time) between both works and are thus in the range [0-1]. By including both the physical and time overlap, only works that score well on both have a significant impact in the algorithm.

2) *Street overlap*

The second evaluation scores two works that do not overlap physically, but are close to each other, e.g. located in the same street.

$$score = (timeoverlap * p)^{f} \tag{3}$$

As discussed earlier, works that overlap physically can benefit from reduced digging costs; advantages for works that are executed in the same street are less straight-forward but not less important. Working twice in the same street, even not on exactly the same location, may result in shutting down that street twice. By executing both works at the same time, total traffic hinder may be reduced. Further, in the long run, utility operators may reach a point when cooperation is sufficiently organized which may allow to share equipment (e.g. signalisation, excavation cranes).

IV. PROPOSED SOLUTION – MULTI-OBJECTIVE APPROACH

The evaluation model approach as discussed III has been implemented using a genetic algorithm. Genetic algorithms are search algorithms, which use techniques found in natural evolution (Figure 4). Within the algorithm, the group of possible solutions (the population) evolves generation after generation, using three basic actions: survival of the fittest (selection), crossover and mutation. Selection ensures that the best solutions are selected to breed offspring (using crossover) and in the meantime that the worse solutions are removed from the population. Finally mutation slightly changes the solutions in an attempt to improve them.

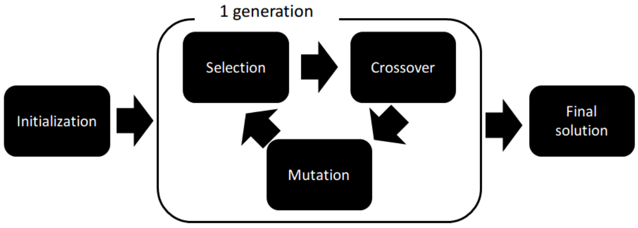

Figure 4: Internal elements of a genetic algorithm

As mentioned in section, II we are currently looking for a *good* solution (while not really requiring the *optimal* solution) to serve as input for discussion for the utility providers. Since a genetic algorithm has a pool of solutions, more than one planning can easily be suggested The synergistic model approach could have be implemented using another type of search heuristic; though for now a genetic algorithm has been used, as a mean to validate the proposed synergy evaluation model.

V. CASE RESULTS

Using the proposed algorithm, we have calculated two cases using realistic data of two urban areas in Belgium. Case I contains a total of 376 planned works, Case II a total of 295. These cases are further discussed using a number of parameters in the next paragraphs.

Firstly we look into the number of works, the number of works in an overlap (either physical or located in the same street) and the number of works executed in synergy in both the original and optimized planning. We assume for a work to qualify as 'executed in synergy', it requires 25% time overlap with another work. For physical overlaps an additional requirement of 25% physical overlap is in place.

Secondly, we look into the total number of weeks of actual cooperation for all projects which are executed in synergy. E.g.: two projects of each 10 weeks overlap 50% in time, thus 5 weeks of cooperation are counted. This number is as important as the number of synergy projects. Two solutions may have exactly the same number of synergy projects, but the actual time overlap between both can still differ a lot. E.g. two projects of each 10 weeks overlap either 50% or 80% in time. In both results we have two synergy projects, however the number of cooperation weeks are respectively 5 and 8 weeks.

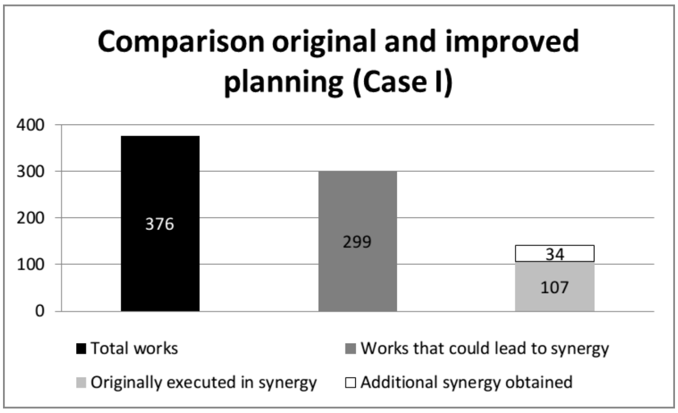

Figure 5: Case I results show a synergy gain of 32%.

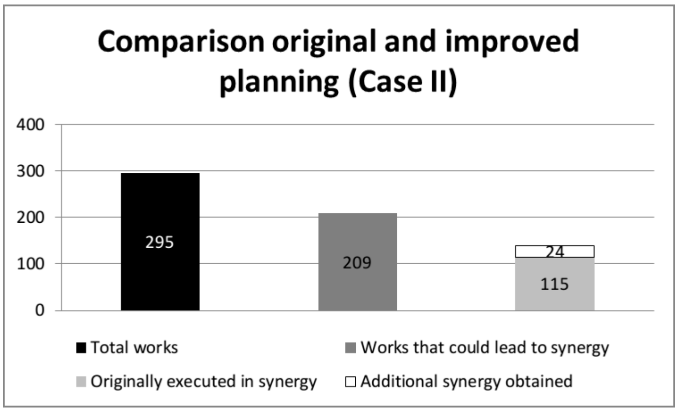

Figure 6: Case II results show a synergy gain of 21%.

Table 2: Summarized case result results

Result	Case I	Case II
Increase in synergy project	32%	21%
Increase in cooperation weeks	46%	25%

Figure 5 and Figure 6 show the results of both calculated cases, Table 2 summarizes the use case results. The synergistic model leads to clear synergy gains in both cases: in both cases there is a clear increase in the number of projects executed in synergy (31% and 21%). When looking into the total number of weeks of cooperation we see even bigger increases (46% and 25%). This suggests that the synergistic model not only finds new areas where cooperation is possible (more synergy projects), but also manages to optimize the planning in areas where cooperation was already planned (a larger increase in number of weeks than number of projects).

The first case clearly has even better results than the second one. The reason behind this is easy enough, case I is bigger and contains more works with any overlap (either physical or street segment); as a direct result more combinations of works are possible and more synergy can be found.

VI. Discussion

The proposed approach, the developed algorithm and the case results have been presented for a number of utility providers in Belgium, followed by an extensive discussion which has taught us a number of real-life implications that should be considered when further developing this synergistic model. In the next paragraphs we discuss each of these and discuss how the synergistic model can be improved.

A. Sensitivity analysis and the preferences of the utility operators

In section IV we have discussed the default values for the evaluations, changing these will obviously impact the results as shown in section V. Decreasing the penalties of the planning evaluations (allowing larger deviations from the original planning) or increasing the scores of the overlap evaluations (and thus rewarding synergy additionally) will lead to even more synergy projects and cooperation weeks while deviating largely from the original planning. The values of each should be discussed with the utility operators in order to find an optimal configuration. Additionally, to show the real impact of these parameters, sensitivity analysis on top of the synergistic model could be performed.

B. Validation of the genetic approch using LP

As discuss in IV, the proposed synergistic model has been implemented using a genetic approach mainly as a prototype. Due to the currently implemented evaluations (as discussed in III.B and III.C) the problem is a non-linear problem, meaning that an (I)LP approach was no alternative. However, with only minor adjustments, this problem can entirely be stated as a linear problem, this would offer the possibility to test the quality of the optimized planning as found using the genetic algorithm with a solution calculated using LP.

C. Modeling of the traffic impact on the urban environment

In the current version of the algorithm, we have not included actual hinder in the urban environment. The reason for this is simple enough; the data which was provided contained only a rough representation of the location of the works. If the input information is sufficiently detailed (either by providing the location of construction sites more accurately or by adding meta-information which indicates which parts of a road are impacted: entirely, only one driving directing, only footpath, etc.) it would be possible to derive when streets are blocked, which traffic diversions are required and all together make a prediction how the newly generated planning will impact the traffic in the urban situation. A number of various approaches were devised to do so:

- A first approach consists of defining/detecting routes that are most important, in other words the routes that have the biggest impact on traffic flows if interrupted. By mapping the road works on these routes, it would be possible to see how many times each route is interrupted. This approach however requires situation-specific (city-specific) knowledge.

- A second approach consists of scoring all roads based upon their importance (e.g. highway, intermediate, local). By again mapping the road works (and possibly diversions) on the scored roads, an additional single-actor evaluation could be defined which scores the impact of each road interruption. Using this approach, interrupting the same local street twice would be penalized less than interrupting an intermediate street twice. Roads can be scored based upon traffic figures or using its location (e.g. distance to the city center or to the nearest highway).
- A final approach defines combinations of road interruptions that are not allowed; this way possible deadlocks in the traffic flows can be avoided, e.g. two ramps to the same highway or two main roads to the city center should never be interrupted on the same moment. Manual input for this approach may be required.

D. Inclusing of cooperation/transaction costs in cost-based approach

As discussed in III, at this point in time, no financial information of the works or the utility providers is provided. This resulted in the fact that having a purely cost-based approach was not possible. Because of this, cooperation/transaction cost such as discussed in [8]-[10] have not been considered in the synergy evaluation model. In other words, currently we suppose cooperation between different utility operators is always beneficial, without considering any overhead costs.

Switching over to a cost-based approach, in which the actual financial gains and costs are modeled, could lead to an even more detailed result, showing that some level of cooperation (e.g. a minimal amount of works per year executed in synergy) is required to obtain financial gains for the utility providers involved. Additionally, if worse comes to worse, and in some scenarios cooperation has little to no economic benefits for the involved utility providers, the impact on the urban area (as discussed in the previous paragraph) might show that still large amounts of nuisance can be avoided in the city environment which will directly lead to additional benefits for the city.

E. Why should a larger utility operator match his planning with a much smaller one?

By default, the weight of each utility provider in the left pillar (single-actor evaluations) is the same, see section III. In other words, the planning and budget of each utility provider is considered as important. In other words a smaller operator has as much impact in the resulting planning as a larger operator.

There is more than one way to look at this issue. From an outsiders' perspective the default approach looks fair as each operator is considered equal. From a pure practical point it may make less sense: large companies have a more complex administration, which makes it harder to alter the planning (which would imply giving them a higher weight in the algorithm, so their planning is considered more important). Whether smaller/bigger utility operator should be weighted differently may even have to be decided on a region-by-region basis.

Whether or not to alter the weights is not a simple discussion of right and wrong and has many points of view, of which we have supplied only some.

VII. Conclusions

In this paper we have presented a genetic algorithm, implementing a synergistic evaluation model, which is capable of generating a synergistic multi-actor planning. As input for the algorithm we use the planning as supplied by the different actors and a set of restrictions (time windows), configurable per type of work and per actor. The proposed algorithm scores each new planning using two sets of evaluations: the first set evaluates the planning per actor, while the second set evaluates the obtained synergies (either two works that physically overlap or two works that do not overlap physically but are located in the same street).

The model has been used to calculate a new planning for two cases which respectively yield 32% and 21% more synergy projects compared to the original planning. On top of these additional synergy projects, the algorithm also obtained respectively 46% and 25% more weeks of work executed in cooperation.

In the future, the synergistic evaluation model can be further extended with points as discussed in section VI: By switching over from a point-based system to a cost-based system more detailed results can be obtained. Additionally by simulating the traffic impact in the urban environment, a trade-off between the cost of cooperation and less urban traffic impact can be made.

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